Materials of the Universe (MotU)

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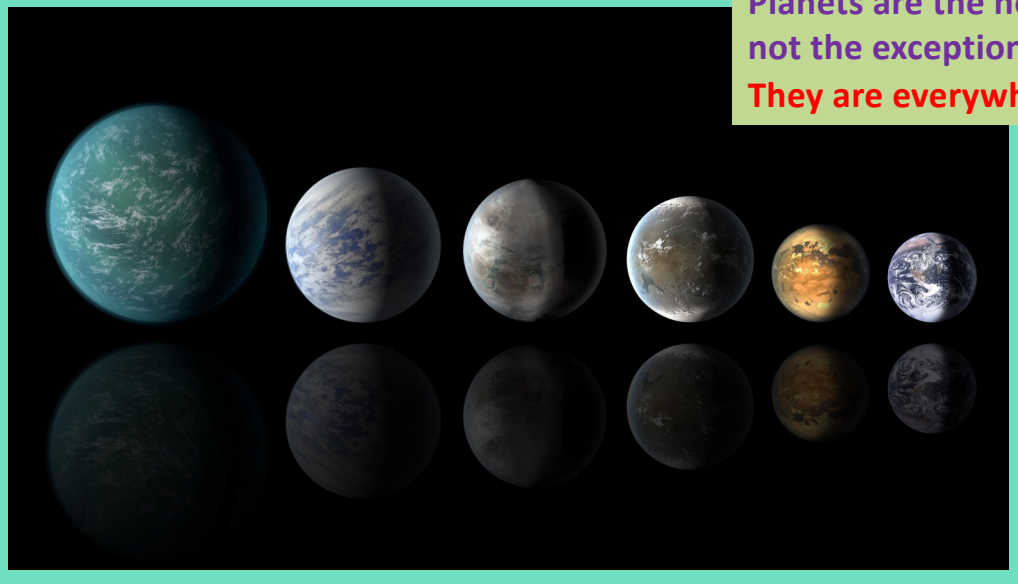


Planets are the norm not the exception.
They are everywhere.

PARADIGM SHIFTS

- Complexity of the solar system
- Exoplanets
- Privatization of space exploration
- New NASA and internatinal missions

- The universe is exciting and will become more so during the next decades.
- Intellectual excitement, money and jobs.
- Science fiction becomes science and technology

What we need- Materials of the Universe

- Unify cosmology, astronomy, geochemistry with chemistry, physics and materials science to understand planets
- Planet-inspired new materials
- Better materials for space exploration including future manned missions

This seminar series gives a taste of the breadth of the field

Given this dazzling diversity of celestial bodies:

We are freed from the tyranny of one geotherm and one planetary composition. The wealth of likely planets and moons provides a huge classic inverse problem in materials science.

Based on scant evidence of size, density, and properties, as well as our knowledge and prejudices about the composition and evolution of the universe, what compositions, phases, and chemistries are possible for a given planet?

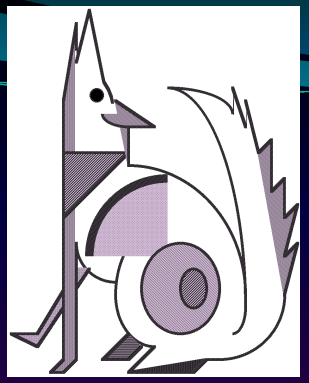
Types of planets and moons

- Earthlike
  - Super and mini earths
  - Why are Venus, Earth, Mars so different? Were they ever more similar?
  - Cores, magnetic fields, tectonics
  - Different P,T,X regimes
  - Cold worlds are dynamic too
- Dirty cold iceballs
- Waterworlds
- Carbon-rich planets with diamond a major phase
- Large gaseous planets - from gas to fluid to metallic states to plasma to failed stars
- Dynamic moons - geysers, methane lakes, strange ices, organics….

Some examples of unexpected variety in the solar system

- Mercury - highly reducing conditions, metals, and sulfides, intense cratering, no atmosphere
- Venus - dense corrosive acidic CO_2-rich atmosphere, 93 bars and 467 ^oC at surface
- Earth - past, present, future, role of life in planetary evolution, atmosphere, and climate
- Mars - very thin atmosphere, oxidized surface, maybe more hospitable to life in the past, how much water at present
- Jupiter and Saturn - from gas to metallic hydrogen to plasma, maybe a chemical factory in the upper atmosphere (i.e. the Red Spot). Many moons.
  - Titan - dense atmosphere, hydrocarbon lakes
  - Enceladus - geysers- is there a dep liquid water layer, even life
- Comets and Asteroids - did they bring water and organics and even life to Earth
- Neptune - very dense atmosphere, high winds, storms

Navrotsky pedigree



- B.S., M.S. Ph.D Univ of Chicago
- Physical chemist by training, solid state chemist and geochemist by profession
- Postdoc in Germany and at Penn State
- First faculty position, ASU 1969-85
- Princeton 1985-97
- UC Davis 1997-20019
- Returned to ASU as Professor in SMS and SEMTE and Director, Navrotsky-Eyring Center for Materials of the Universe, Oct. 2019

Why I Count Calories for a Living

- They are fascinating
  - Energetics whisper secrets of the strength of chemical bonds
  - Entropies sing of vibrating atoms, moving electrons, and structural disorder
  - Systematics have predictive power
- They pay
  - thermodynamic data are essential to good materials processing
  - Environmental science needs thermodynamics, both for issues of stability and as a starting point for kinetics
  - Mineralogy, petrology, and deep Earth geophysics need thermodynamic data.

Calorimetry Measures

- Heat capacities
- Heats of phase transitions'
- **Heats of formation**

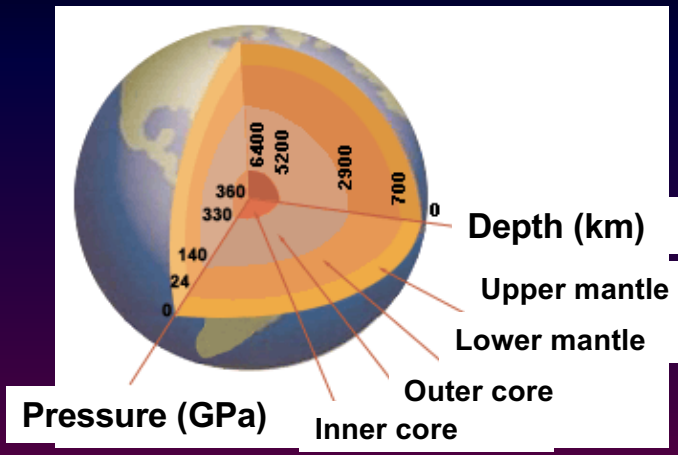
From these data one calculates

Enthalpies, entropies, free energies

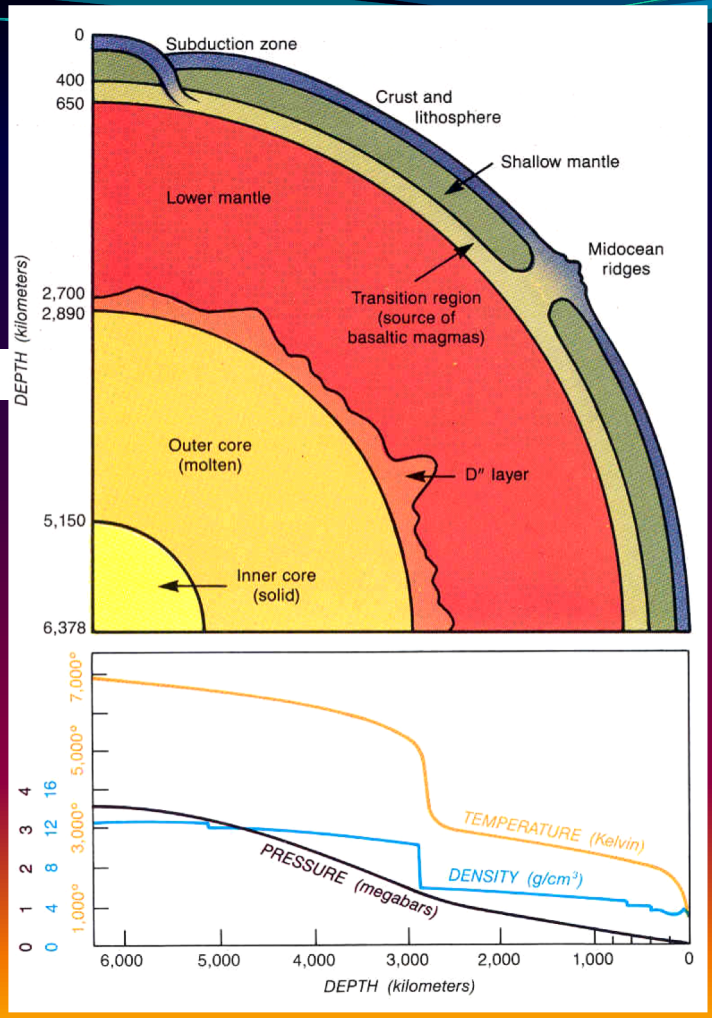
- Solubililities
- Phase diagrams
- **Petrologic and geochemical processes**
- **Materials synthesis and compatibility**

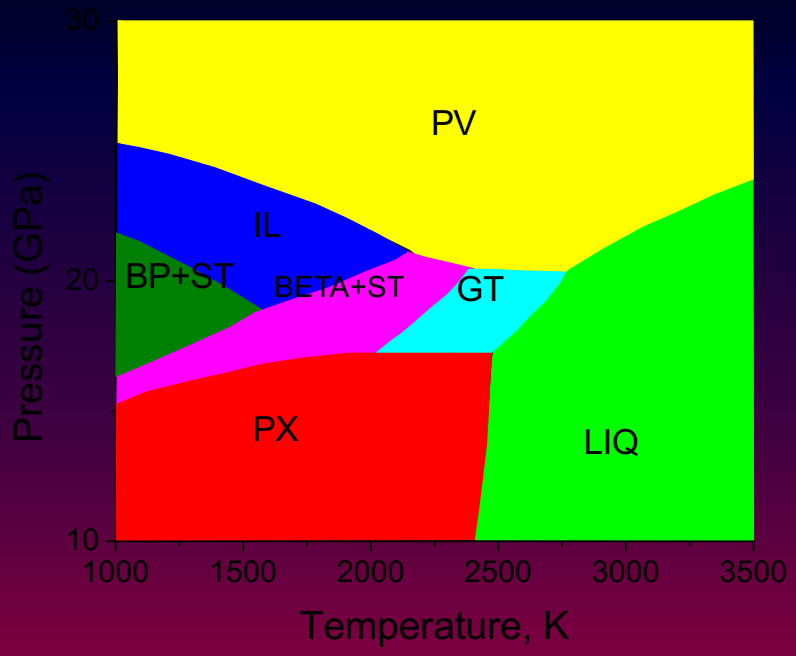
Some examples of my thermodynamic work relevant to planetary science

- "Internally Consistent Thermodynamic Data and Equilibrium Phase Relations for Compounds in the System MgO-SiO_2 at High Pressure and High Temperature," Y. Fei, S. K. Saxena, and A. Navrotsky, *J. Geophys. Res.*, 95, 6915-6928 (1990).
- "Thermodynamic Stability of Hydrous Silicates: Some Observations and Implications for Water in the Earth, Venus and Mars," A. Navrotsky and K. Bose, in "Volaties in the Earth and Solar System," K. A. Farley, Ed., *Amer. Inst. Phys. Conf. Proc.*, 341, 221-228 (1995).
- "Possible Presence of High-pressure Ice in Cold Subducting Slabs," C. R. Bina and A. Navrotsky, *Nature*, 408, 844-847 (2000).
- "Jarosite Stability on Mars," A. Navrotsky, F. L. Forray, and C. Drouet, *Icarus*, 176, 250-253 (2005).
- "A Clathrate Reservoir Hypothesis for Enceladus' South Polar Plume," S. W. Kieffer, X. Lu, C. M. Bethke, J. R. Spencer, S. Marshak, and A. Navrotsky, *Science*, 314, 1764-1766 (2006).
- "Carbon Substitution for Oxygen in Silicates in Planetary Interiors," S. Sen, S. J. Widgeon, A. Navrotsky, G. Mera, A. Tavakoli, E. Ionescu, and R. Riedel, *Proc. Natl. Acad. Sci.* 110, 15904-15907 (2013).



Concentric shells of different phase assemblages with sharp discontinuities between them
Olivine-spinelloid-spinel at 400 km
Spinel- perovskite + periclase at 670 km
Core-mantle boundary





Phase relations in $MgSiO_3$ composition (PX – pyroxene, BETA -wadsleyite, LIQ –liquid, SP –spinel, ST –stishovite, IL – ilmenite, PV -perovskite (After Fei Saxena, Alexandra Navrotsky, 1990)

Navrotsky- Major Current Projects

- Actinides
- Lanthanides and critical materials
- Fuel cell and battery materials
- Ultra high T processes
- Nanomaterials
- Open frameworks and confinement

UCDAVIS
PETER A. ROCK
Thermochemistry
Laboratory

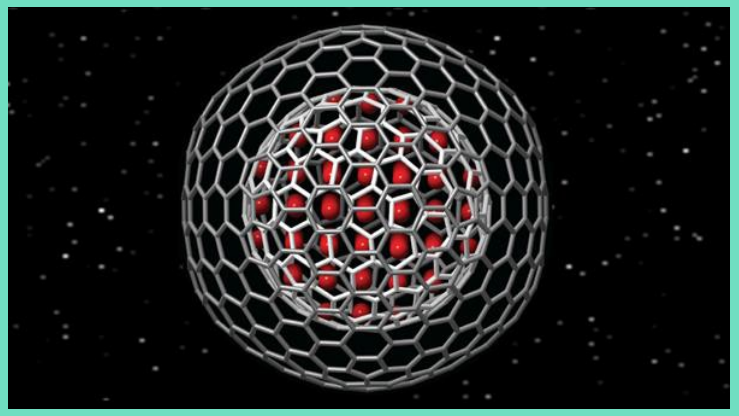
MotU Opportunities for Chemistry, Physics, Materials Science, Engineering

- Materials for space exploration and remote sensing
- Materials processing in space and on planets
- Energy and resources in extraterrestrial environments
- New materials discovery
- Fundamental understanding of extreme conditions- hot, cold, high pressure, low pressure…..
  - Experiment
  - Theory

Advanced Materials Initiatives
Arizona State University

ASU's Materials of the Universe Initiative

A paradigm shift in understanding the universe



Materials and Space Exploration

- Exoplanetary Chemistries (a Staggering diversity)
  - Apply modern materials research methods
  - Exoplanets as grand complex materials problems
- Materials Discovery
- Materials Under Extreme Conditions
- Radiation and Materials
- Databases on Materials and Space Exploration

cross-disciplinary and intercollege MOTU Center

- **Faculty recruitments and seed funding**
- **Seek funding**
- **Joint Research**
- **Student opportunities**
- **Courses**

THERMODYNAMICS CONSORTIUM

A triad of experimental thermodynamics, structural investigation and theory/computation

WHO ARE WE?

Experimentalists who interact with a wider circle of computational and structural scientists to understand the fundamental science of complex materials and apply this understanding to a rich variety of scientific and technological problems.

- 200 participants
- 13 countries and 4 continents
- 40 universities
- 5 companies

THE NEED

Thermodynamics for:

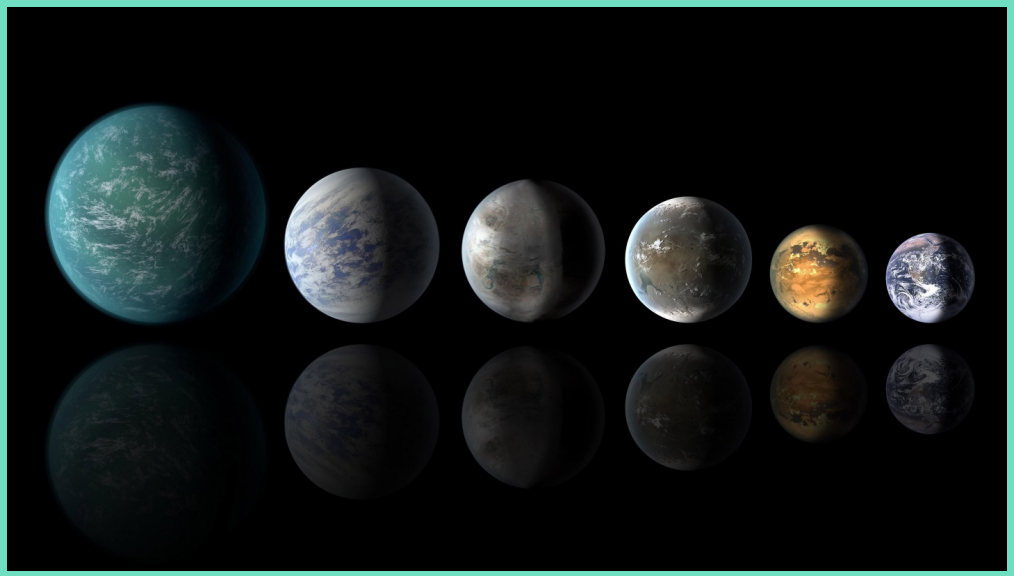
- **materials science**
- **earth and planetary science**
- **environmental science**
- **industry, technology, medicine**

https://www.thermocon.org/

THE GOALS

- To provide easy access to collaborations.
- To exchange best practices and scientific discoveries among the participants.
- To guide and support young researchers

- **To work with database developers and users to create an interactive, growing and easily updated reference database**
- **To enhance communications with manufacturers of scientific measurement equipment and industry in general, who will respond to the needs of their customers**
- **To organize workshops, short courses, targeted symposia at conferences, topical special issues of journals.**



Different breeds, behavior sometimes similar, sometimes different , seek causes and commonalities